Lepton Flavour Violation at LHCb

$\tau \to 3\mu, B \to \mu^{\pm} e^{\mp}$ and $B \to h\mu^{\pm} e^{\mp}$

(What other decays could be interesting?)

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1. (intro:no models, but operators...)

2. are these promising modes where to find LFV?
   - bounds and future sensitivities of these/other processes
   - take three parametrisations of $\mathcal{L}_{eff}$, estimate reach of these/other processes
     $\Rightarrow$ most sensitive modes vary with parametrisation

   $\Rightarrow$ YES

3. signal, backgrounds, etc...
   - short vs long distance in $\tau \to 3\mu$, and $\tau \to \mu\gamma$
   - B decays

Caveat: *No model predictions !*

recent reviews:
Paradisi, Feldmann
Hirsch,...

(LFV $\equiv$ interaction changing charged lepton flavour at a point
$\neq$ ν oscillations
$\simeq$ FCNC among d-type quarks)

The relation of lepton flavour to BSM, vs quark flavour to BSM, is *different* :

1. lepton flavour conserved in SM $\Rightarrow$ LFV is a signal of New Physics

2. we know $m_\nu \neq 0 \Rightarrow$ *New Physics in the leptons!*

   $\Rightarrow$ there is LFV. Just we don't know the rate.

Caveat: *No Models!*

recent reviews:
Paradisi, Feldmann
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The relation of lepton flavour to BSM, vs quark flavour to BSM, is *different* :

1. lepton flavour conserved in SM $\Rightarrow$ LFV is a signal of New Physics

2. we know $m_\nu \neq 0 \Rightarrow$ *Beyond the Standard Model in the leptons!*

   $\Rightarrow$ there is LFV. Just we don't know the rate.

3. many models fit m_ν and LFV data, and give diverse predictions ...
   $\Rightarrow$ parametrise with Effective Lagrangian

Parametrising BSM : the effective Lagrangian

Suppose New Physics at $\Lambda > m_W$. Parametrise via (some linear combo of) SM-gauge invar operators at dimension 6 and/or 8:

$$
\begin{array}{lcrl}
(\overline{\ell}_i\gamma^\mu\ell_j)(\overline{\ell}_k\gamma_\mu\ell_l) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_L\tau)(\overline{\mu}\gamma_\alpha P_L\mu) & \\
(\overline{\ell}_i\tau^I\gamma^\mu\ell_j)(\overline{\ell}_k\tau^I\gamma_\mu\ell_l) & \longrightarrow & \text{``} & \\
(\overline{e}_i\gamma^\mu P_R e_j)(\overline{e}_k\gamma_\mu P_R e_l) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_R\tau)(\overline{\mu}\gamma_\alpha P_R\mu) & \text{V} \pm \text{A} \\
(\overline{\ell}_i e_j)(\overline{e}_k\ell_l) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_{L,R}\tau)(\overline{\mu}\gamma_\alpha P_{R,L}\mu) & \\
 & & & \\
(\overline{\ell}_i H e_j)(\overline{\ell}_k H e_l) \text{ (dim 8)} & \longrightarrow & (\overline{\mu}P_{L,R}\tau)(\overline{\mu}P_{L,R}\mu) & \text{S} \pm \text{P}
\end{array}
$$

$$
\begin{array}{lcrl}
(\overline{\ell}_i\gamma^\mu\ell_j)(\overline{q}_k\gamma_\mu q_l) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_L e)(\overline{b}\gamma_\alpha P_L d) & \\
(\overline{\ell}_i\tau^I\gamma^\mu\ell_j)(\overline{q}_k\tau^I\gamma_\mu q_l) & \longrightarrow & \text{``} & \\
(\overline{e}_i\gamma^\mu P_R e_j)(\overline{d}_k\gamma_\mu P_R d_l) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_R e)(\overline{b}\gamma_\alpha P_R d) & \text{V} \pm \text{A} \\
(\overline{\ell}_i d_l)(\overline{d}_k\ell_j) & \longrightarrow & (\overline{\mu}\gamma^\alpha P_{L,R} e)(\overline{b}\gamma_\alpha P_{R,L} d) & \\
 & & & \\
(\overline{\ell}_i e_j)(\overline{d}_k q_l) & \longrightarrow & (\overline{\mu}P_{L,R} e)(\overline{b}P_{L,R} d) & \text{S} \pm \text{P}
\end{array}
$$

Want to know: how big can be coeff of these operators?

Where to look for LFV? Start from what we know = bounds

some processes	current sensitivities
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$
$BR(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$
$BR(\tau \to \mu e^+ e^-)$	$< 1.8 \times 10^{-8}$
$BR(\tau \to \mu K_S)$	$< 2.3 \times 10^{-8}$
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$
$BR(K^+ \to \pi^+\mu^+ e)$	$< 1.3 \times 10^{-11}$
$BR(B_d \to \tau^\pm e^\mp)$	$< 2.8 \times 10^{-5}$
$BR(B \to e^\pm \mu^\mp)$	$< 6.4 \times 10^{-8}$
$BR(B \to \pi^0(K_0)\mu^\pm e^\mp)$	$< 1.4 \times 10^{-7}(2.7 \times 10^{-7})$
$BR(B^+ \to K^+\tau\bar{\mu})$	$< 7.7 \times 10^{-5}$

... generation diagonal motivated? (Or not, since lepton mixing angles large)

Applying exptal bounds to dim 6 operators with coefficient $1/(16\pi^2\Lambda^2)$

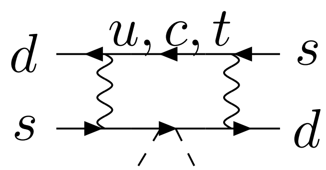
process	bound	lower bd on dim 6 scale, @ loop
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$	48 TeV
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$	14 TeV
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	2.8 TeV
$BR(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	0.8 TeV
$BR(\tau \to \mu e^+ e^-)$	$< 1.8 \times 10^{-8}$	0.8 TeV
$BR(\tau \to \mu K_S)$	$< 2.3 \times 10^{-8}$	0.5 TeV
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	25 TeV$(V \pm A)$
		140 TeV$(S \pm P)$
$BR(B \to \tau^{\pm} e^{\mp})$	$< 2.8 \times 10^{-5}$	0.3 TeV$(V \pm A)$, 0.6 TeV$(S \pm P)$
$BR(B \to e^{\pm}\mu^{\mp})$	$< 6.4 \times 10^{-8}$	3 TeV $(S \pm P)$
$BR(B \to K^0 \mu^{\pm} e^{\mp})$	$< 2.7 \times 10^{-7}$	1.1 TeV
$BR(B^+ \to K^+ \tau\bar{\mu})$	$< 7.7 \times 10^{-5}$	0.3 TeV

μ, K searches more sensitive to new particles with "democratic" flavour interactions

But if LFV operators arise via a loop at dim 8? (coefficient $v^2/(16\pi^2\Lambda^4)$)

process	bound	scale (dim 6, loop)	scale (dim 8, loop)
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$	48 TeV	2.9 TeV
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$	14 TeV	1.5 TeV
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	2.8 TeV	0.7 TeV
$BR(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	0.8 TeV	0.4 TeV
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	25 TeV$(V \pm A)$	2.1 TeV$(V \pm A)$
$BR(B \to \tau^\pm e^\mp)$	$< 2.8 \times 10^{-5}$	0.3 TeV$(V \pm A)$	0.2 TeV
$BR(B \to e^\pm \mu^\mp)$	$< 6.4 \times 10^{-8}$	3 TeV $(S \pm P)$	0.7 TeV
$BR(B \to K^0 \mu^\pm e^\mp)$	$< 2.7 \times 10^{-7}$	1.1 TeV	0.4 TeV
$BR(B^+ \to K^+ \tau\bar{\mu})$	$< 7.7 \times 10^{-5}$	0.3 TeV	0.3 TeV

New particles which contribute at one loop
to dim eight LFV operators, with "democratic" couplings,
could be accessible to colliders,
and found in all rare decays.



But flavoured couplings we know are not 1?

Lets suppose

1. a mass scale for new particles $\sim$ TeV
2. tree diagrams (no factors of $1/(16\pi^2)$)
3. flavoured fermion couplings $\propto \sqrt{\mathrm{SM\ masses}}$, so 4-fermion operator coefficient

$$\epsilon^{ijkl} \propto \sqrt{\frac{m_i m_j m_k m_l}{v^4}} \quad , \quad i,j,k,l \text{ any SM fermion}$$

Cheng Sher
extra dim ...

estimate rates assuming no additional (eg chiral) suppression factors...
(except when estimate is to big)

numbers ~ Carpentier Davidson

Current bounds vs naive hierarchical expectations

process	bound	expectation
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$	$\sim 2 \times 10^{-14}$ (avec mass insertion)
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$	$\sim 10^{-17}$ (long distance loop)
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 8 \times 10^{-11}$ (avec mass insertion)
$BR(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\sim ?10^{-14}$ (long distance loop)
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	$\sim 5 \times 10^{-15}$ $(S \pm P)$
		$\sim 10^{-17}$ $(V \pm A)$
$BR(B \to \tau^{\pm} e^{\mp})$	$< 2.8 \times 10^{-5}$	$\sim 4 \times 10^{-15}$ $(S \pm P)$
$BR(B_s \to \tau^{\pm} \mu^{\mp})$		$\sim 10^{-11}$ $(S \pm P)$
$BR(B \to e^{\pm} \mu^{\mp})$	$< 6.4 \times 10^{-8}$	$\sim 4 \times 10^{-16}$ $(S \pm P)$
$BR(B \to K^0 \mu^{\pm} e^{\mp})$	$< 2.7 \times 10^{-7}$	$\sim 10^{-15}$ $(V \pm A)$
$BR(B^+ \to K^+ \tau \bar{\mu})$	$< 7.7 \times 10^{-5}$	$\sim 10^{-11}$

1. tree level
2. a mass scale for new particles $\sim$ TeV
3. flavoured couplings $\propto$ SM masses:

$$\lambda_{ij} \simeq \sqrt{\frac{m_i m_j}{v^2}} \quad , \quad i, j \text{ any SM fermion}$$

Parenthese: τ in final state?

1. New Physics (maybe?) more likely in 2nd,3rd gen. (few searches, large yukawas)

$$\Rightarrow \text{is } B \to K\tau^{\pm}\mu^{\mp} \text{ possible?} \quad (\text{or } B_s \to \tau^{\pm}\mu^{\mp})?$$

(only bounds I know on $\bar{b}s\bar{\tau}\mu$ vertex are V_{cb} and BABAR $BR(B^+ \to K^+\tau\bar{\mu}) < 7.7 \times 10^{-5}$)

For Cheng-Sher ansätz with $\Lambda \sim v$, expect BRs $\sim 10^{-8}$.

2. on the other hand...leptonic mixing angles (due to NP) are large. Maybe NP is hierarchical for quarks, not for leptons...

(Kaons are specially sensitive to $S \pm P$: compare sensitivity of $B_s \to \tau^{\pm}\mu^{\mp}$ and $K_L \to e^{\pm}\mu^{\mp}$ to NP with hierarchical couplings:

$$\frac{BR(B_s \to \tau\bar{\mu})}{BR(K_L \to e\bar{\mu})} \simeq \frac{f_B^2 m_s^2}{f_K^2 m_b^2}\frac{|\epsilon^{bs\tau\mu}|^2}{|\epsilon^{sd\mu e}|^2}$$

Question was: in what processes is LFV likely to appear?

varied three generic properties of New Physics:

1. loop order at which flavour change appears

2. dimension of operator

   various LFV processes sensitive to "tasteless" dimension 8 operators

   (K and μ physics more sensitive to "tasteless" dimension 6)

3. pattern/hierarchy in couplings

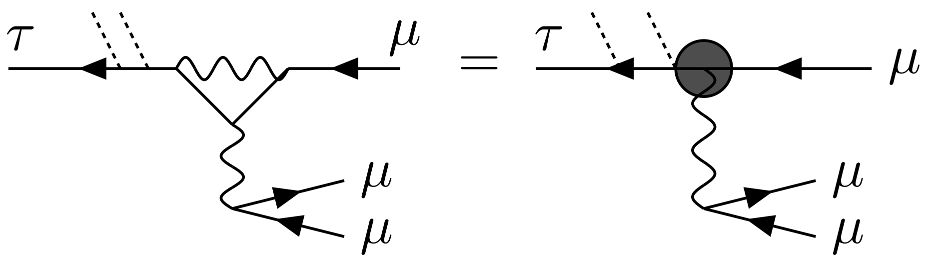
   hierarchical couplings favour LFV involving τs and bs

find they favour different processes

$\Rightarrow$ mix and match — large parameter range where your favourite decay is most sensitive to LFV. (c'est à dire: restrictive $\mu \to e\gamma$ bound does not preclude $\tau \to 3\mu$, and all LFV B decays are interesting...)

$\tau^\pm \to \mu^\mp \mu^\pm \mu^\pm$: long distance — does it matter?

1. what is it?



2. why could be the problem?
   Dalitz plots of various contact interactions are $\sim$ flat(see,eg 0707.0988). This is not. (?does phase space distribution matter for backgrd rejection?)

3. does it arise?
   No(?): dipole operator is bounded by $\tau \to \mu\gamma$. Contribution to $\tau \to 3\mu$ has additional e^2 and $1/4\pi^2$ for phase space...suppressed below $BR \sim 10^{-8}$.

NO

Summary

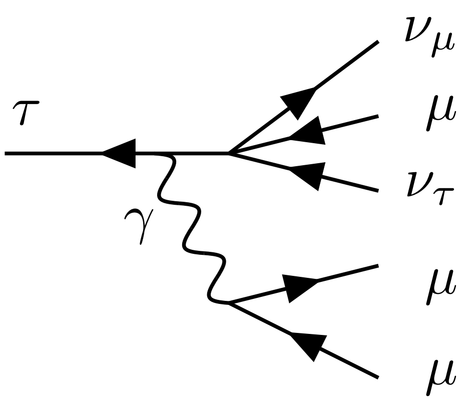
1. are $\tau \to 3\mu, B \to \mu^\pm e^\mp$ and $B \to h\mu^\pm e^\mp$ promising modes where to find LFV?
   $\Rightarrow$ YES

2. What other decays could be interesting?

$$B \to K\tau^\pm\mu^\mp \; ? \quad (\text{or } B_s \to \tau^\pm\mu^\mp)?$$

Back Up

$\tau^\pm \to \mu^\mp\mu^\pm\mu^\pm$: what about?



??

$$BR(\tau \to \mu\bar{\nu}_\mu\nu_\tau\gamma) = 3.6 \times 10^{-3}$$
$$BR(\tau \to e\bar{\nu}_e\nu_\mu\gamma) = 1.4 \times 10^{-2}$$
$$BR(\mu \to e\bar{\nu}_e\nu_\tau\gamma) = 1.75 \times 10^{-2}$$
$$BR(\mu \to e\bar{\nu}_e\nu_\tau e\bar{e}) = 3.4 \times 10^{-5}$$

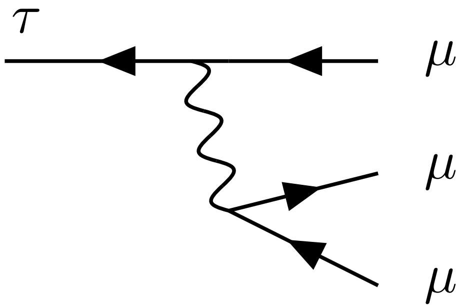
guessing $BR(\tau \to \mu\bar{\nu}_\mu\nu_\tau\mu\bar{\mu})$

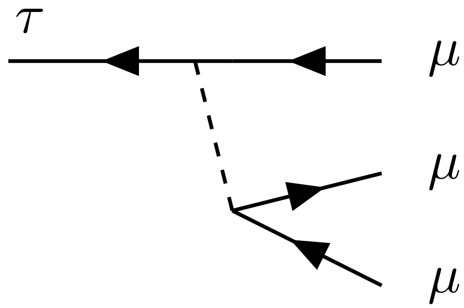
1. γ costs $e^2 \times 1/(4\pi^2) \sim 3 \times 10^{-3}$
   need also some IR logm_ℓ/μ_{IR} (to get μ BR, and τ ratios)

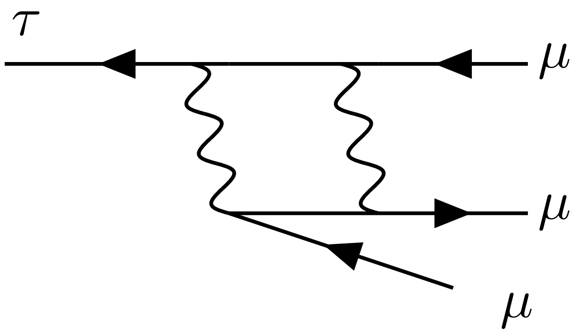
2. e^+e^- costs $e^4 \times 1/(4\pi^2)^2 \sim 10^{-5}$
   no significant log?

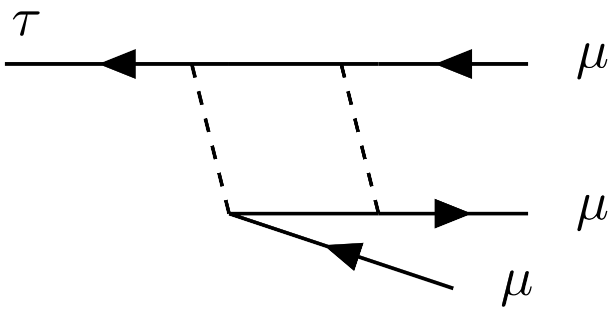
$$\Rightarrow BR(\tau \to \mu\bar{\nu}_\mu\nu_\tau\mu\bar{\mu}) \sim \text{few} \times 10^{-6}?$$

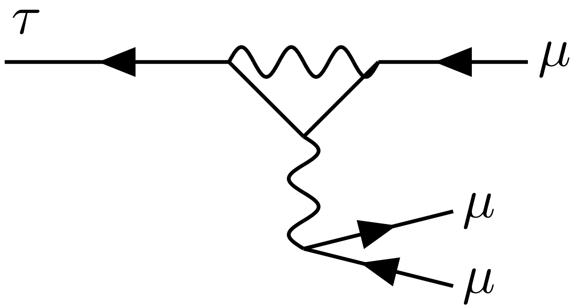
$\tau^{\pm} \to \mu^{\mp}\mu^{\pm}\mu^{\pm}$ — some diagrams



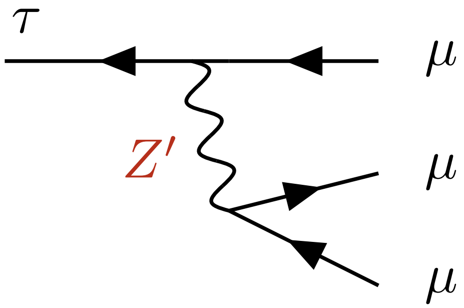


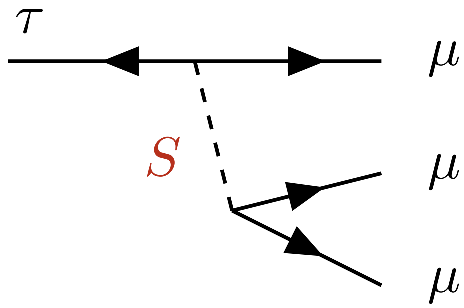


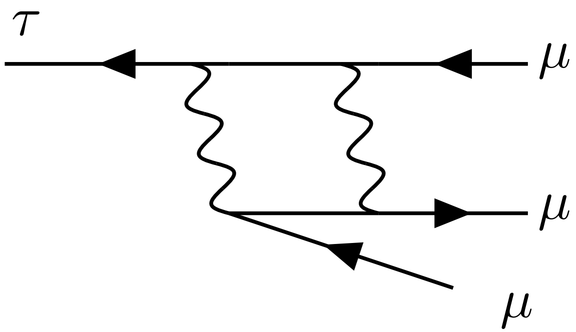


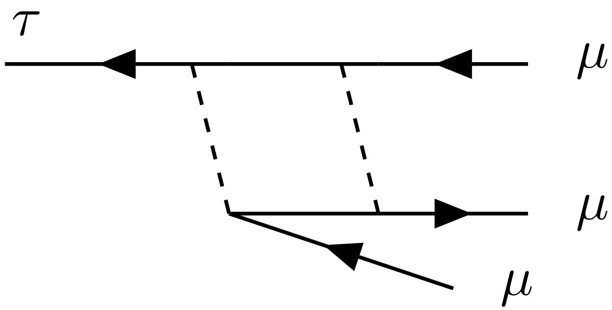


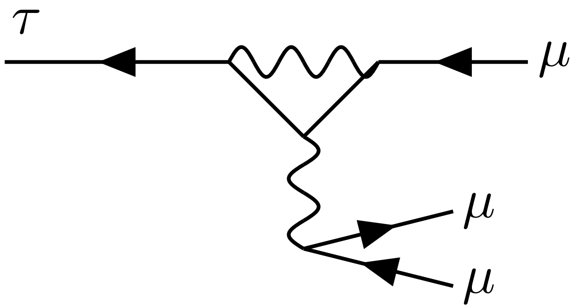
$\tau^{\pm} \to \mu^{\mp}\mu^{\pm}\mu^{\pm}$ — some diagrams



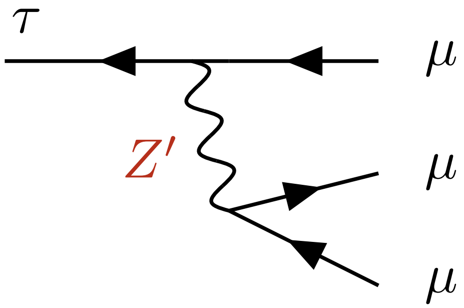


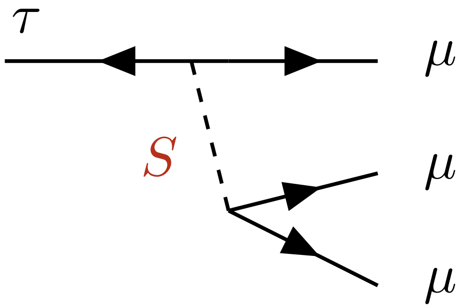


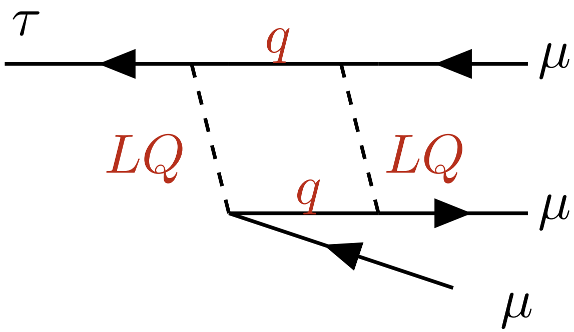


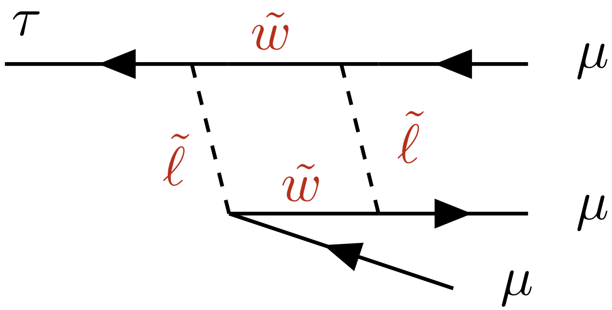


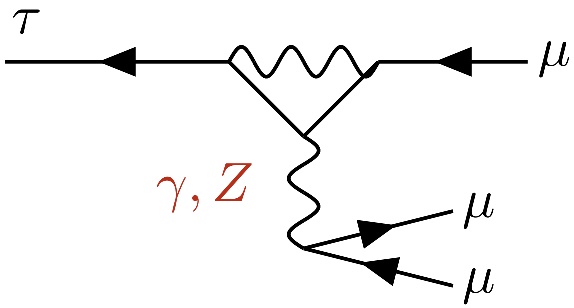
$\tau^{\pm} \to \mu^{\mp}\mu^{\pm}\mu^{\pm}$ — some diagrams











... + many others...